THE SUTURE OF BLOOD VESSELS. IMPLANTATION AND TRANSPLANTATION OF VESSELS AND ORGANS. AN HISTORICAL AND EXPERIMENTAL STUDY.*

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It is only in comparatively recent years that conservative methods have been employed in dealing with the larger blood vessels in the human body. This advance is in a large measure due to the results obtained by the application of modern surgical technic to animal experimentation.

The ligature, which during the middle ages waged a constant warfare with cauterization, compression and other methods of hæmostasis, was toward the end of the eighteenth century recognized as the best method for controlling hemorrhage from large and small blood vessels. Inasmuch as ligation of the large vessels not infrequently gave rise to gangrene and sometimes caused loss of life, this method was not an ideal one. Some years elapsed, however, before further progress was made; then surgeons began to apply the lateral ligature in partial wounds of veins where the continuity of the vessel was not interrupted. This method was first used successfully about the beginning of the nineteenth century, but, as was the case in other branches of surgery, first came into general use after the introduction of antiseptics. The lateral ligature has the disadvantage that it can be used in only a limited number of cases, for if the wound in the vessel is

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large the ligature will produce considerable narrowing of its lumen and there is danger of the ligature slipping. To meet these difficulties various clamps were devised for approximating the edges of venous wounds during the process of healing, but the great objection to this method, although it was a step in the right direction, was that it prevented primary healing of the cutaneous wound.

The Lateral Suture of Veins and Arteries.

The problem was solved by the introduction of the venous suture, which was carried out for the first time successfully by Schede in 1882. This method was later employed in numerous cases and has now come into such general use that almost every surgeon of experience has had occasion to use it.

The beginning of a conservative treatment of arterial wounds antedates by more than a century the first experiments with the lateral suture of veins. In 1759 Hallowel, an English surgeon, at the suggestion of Lambert, who had observed the spontaneous healing of vessel wounds after venesection, sutured an artery in man for the first time. A small wound in the brachial artery was closed by placing a pin through the lips of the wound and passing a thread around it. The patient recovered and the radial pulse remained nearly as strong as that in the other arm.

In 1772 the question of arterial suture was tested experimentally by Asman, who closed wounds in the femoral arteries of four dogs by the same method which Hallowell had employed in man. None of these experiments were successful, and Asman therefore declared the method insecure and dangerous. It was not until 1881, after antisepsis had gained a firm foothold, that arterial suture was again tried in animals, but without the desired result. In 19 cases Gluck sutured longitudinal wounds in the common iliac arteries of large dogs and in the aorta of rabbits, but there was always hemorrhage from the stitch holes and in tying the sutures tears were often made in the vessel wall. To overcome these difficulties he later constructed small ivory clamps, with which the wound in

the artery was closed and which were allowed to remain in situ. In this manner he succeeded in closing a partial wound of an artery with preservation of its lumen. Several years later v. Horoch experimented with arterial suture, but, likewise, with little success.

To Jassinowsky, who published the results of his experiments in 1889 in his inaugural dissertation, belongs the credit of having proven conclusively that arterial wounds can be sutured with preservation of the lumen of the vessel. He avoided the femoral artery, which had been used by previous experimenters, and used the carotids of large dogs, horses, and calves, making longitudinal and transverse wounds in the vessels and then suturing them. The longitudinal wounds varied in length from 3 mm. to 2 cm. and the transverse wounds included ⅓ to ½ of the circumference of the vessel. Of 26 experiments, all were successful except four, and in none of the successful cases was there secondary hemorrhage, thrombosis or aneurysm formation, although some of the specimens were examined as late as a hundred days after the operation.

Jassinowsky attributed his good results to his technic and to the fact that he experimented upon vessels of large caliber. He used fine curved needles and fine silk, the interrupted sutures being placed about 1 mm. apart, including only the media and adventitia and avoiding the intima. As a result of his experiments he reached the following conclusions: (a) The arterial suture heals by first intention; (b) bleeding after operation can be surely and completely avoided; (c) secondary hemorrhage and thrombosis are not to be feared; (d) suture should be done in all recent, clean longitudinal, oblique, and flap wounds of large vessels and in transverse wounds not exceeding one-half the circumference of the vessel; (e) the strictest asepsis is necessary; (f) the suture is easily done.

Murphy in 1897 published the results of numerous experiments with the partial suture of arteries along with other experiments with the resection of arteries.[2] He sutured 11 partial wounds in the abdominal aorta,

[2] Vid. infra.

carotid, femoral and iliac arteries of dogs and two wounds in the carotids of sheep. These were longitudinal and oblique wounds ¼ to ⅝ inch in length and transverse wounds including ⅓ of the circumference of the vessel. Of the 13 sutures 6 were entirely successful, the lumen of the vessels being preserved. In 10 cases a continuous suture of fine silk, including all the coats of the vessel, was used; in one, interrupted silk sutures were used, and in two, kangaroo tendon was the suture material. As the means of provisional hæmostasis Billroth clamps armed with rubber were usually used, sometimes a heavy silk thread twisted and held with the fingers.

As a result of his own and the experiments of others Murphy came to the following conclusions: (a) Besides the most careful asepis, a good technic is necessary for the success of vessel suture; (b) the vessel must be exposed very carefully and a good means of provisional hæmostasis applied; (c) the edges of the wounds must be accurately approximated and bleeding completely stopped; (d) as suture material he recommends silk which should include only the outer coats of the vessel; (e) he recommends the suture of the vessel sheaths and surrounding tissues as a support to the vessel suture.

In 1897 and 1898 SILBERBERG experimented with the arterial suture in dogs. He applied 12 longitudinal and 6 transverse sutures, 10 in the femorals, 6 in the common carotids, and 2 in the abdominal aorta. Five of the longitudinal and 3 of the transverse sutures were quite successful. For a successful suture Silberberg emphasized the importance of an absolute asepsis. As suture materials he used the finest Hagedorn intestinal needles and the finest silk. With the exception of three cases in which he used interrupted sutures, he made use of the continuous suture, which can be applied more rapidly. He does not attach much importance to the question as to whether the suture should or should not penetrate the intima, but thinks that sutures exposed in the lumen may contribute to thrombus formation. He thought a method of provisional hæmostasis, which spares the vessel wall as much as possible, was very important and made use of heavy silk threads which were passed around the vessel and, after being twisted, were held thus by means of clamps. The slight bleeding from the stitch holes is easily stopped by a little compression. As an additional support he recommends the suture of the vessel sheath. Concerning the indications for vessel suture this author says: (a) The wound should be clean; (b) only large vessels, such as the aorta, the carotid, subclavian, axillary and femoral vessels, should be sutured; (c) longitudinal oblique, and transverse wounds, which do not exceed one-third of the circumference of the vessel are adapted to suture.

In 1899 DÖRFLER published a very interesting and instructive paper, describing the results of his experiments with the suture of arteries. Altogether there were 20 experiments, 16 being simple sutures of longitudinal, oblique and transverse arterial wounds with 12 successful results and 4 being sutures of completely divided arteries, which will be described later.[1] As the result of his experiments, Dörfler came to the following

[1] Vid. infra.

conclusions: (a) Arterial suture is only indicated in clean wounds; (b) for temporary hæmostasis the best means are compression with the fingers, strips of gauze twisted together, or clamps armed with rubber; (c) fine needles and a continuous suture of fine silk including all the coats of the vessel should be used; (d) slight pressure upon the suture for a few minutes after its completion will readily stop bleeding; (e) the vessel sheath should also be sutured.

JAKOBSTHAL, who examined Dörfler's specimens histologically, found that the process of healing of arterial wounds proceeds as follows: The incision becomes filled with blood and fibrin, there being only slight deposits within the lumen about the suture and upon the inner aspect of the vessel wound. These deposits are very early, even in the first few days, covered with endothelium. Soon there is an active formation of new connective tissue and blood vessels in the adventitia and to a lesser extent in the media. These make their way into the clot and in a certain measure organize it, thus forming an end-, mes-, and peri-arteritic growth rich in cells. Then there is a retrogressive process; the cells become fewer and less rich in protoplasm, while a fibrous substance appears between them. This substance in the media and adventitia is chiefly connective tissue with a few elastic elements, while in the intima there is an extraordinarily rich new formation of fine elastic lamellæ and fibers which may lead to the formation of a kind of secondary elastica, at least in the region of the scar.

In 1906 DORRANCE published a method of vessel suture, which he claimed to be original with him, but which is almost identical with that described by Clermont in 1901. Dorrance used a continuous mattress suture of fine Pagenstecker's thread with the dropping-back one-half a suture length every third suture, continuing the same suture as a whip-stitch over the everted edges of the artery after completing the mattress suture. With this method he experimented with the closure of wounds in arteries and the union of completely divided arteries.

There were 14 operations in all, nine on horses and five on dogs, and of the 14 wounds 12 suppurated. There were three complete circular and 11 partial transverse, oblique and longitudinal wounds. Ten of the vessels were examined from 2 to 14 days, and the other four from 21 to 42 days after the operation. In seven no thrombus was visible, in five a small mural thrombus was present and in two complete thrombosis. These are remarkably good results considering the number of suppurations. I am inclined to think that, had the specimens been examined at longer intervals after operation, more complete thromboses would have been present, especially when we consider the number of cases in which mural thrombi occurred.

While animal experimentation has shown conclusively that arterial wounds can be sutured successfully, numerous instances of successful suture of accidental wounds of arteries in man have demonstrated the practical value of this pro-

cedure. Such cases have been reported by Heidenhain, Israel, Ssabanejew, Orlow, Lindner, Garré, Seggel, Veau, Heinlein, Baum, Torrence, and others. Up to July, 1902, Schmitz was able to collect 21 cases of lateral sutures of arteries in man, the axillary artery having been sutured seven times, the femoral five times, the popliteal and brachial each three times, the common iliac, common carotid, and internal carotid each once. In 1903 Höpfner collected 30 such cases.

The results of the foregoing experiments on animals and the clinical experience show that for a successful suture the following things are necessary: (a) A very perfect aseptic technic; (b) clean cut wound edges which can be approximated without too much tension; (c) very careful handling of the vessel without stripping its sheath too much.

While there is considerable difference of opinion as to whether silk or catgut is the best suture material, there is little doubt that the former is preferable. It can be obtained in finer sizes, handled much more easily, and sterilized more surely. The needles should be as fine as possible, but whether straight or curved depends upon the location of the vessel to be sutured.

The question as to whether the interrupted or continuous suture should be used, seems to be settled in favor of the latter, which is simpler and can be applied more rapidly. The question as to whether the suture should penetrate all the coats of the vessel or avoid the intima, seems of more importance. While Jassinowsky and others recommend the avoidance of the intima, v. Horoch, Murphy, Dörfler, Dorrance, and others allow their sutures to penetrate the intima, in fact, in suturing veins it is almost impossible to avoid it. By including all the vessel coats the suture is not only simplified, but made more secure.

Various methods have been used for producing temporary hæmostasis, finger pressure, various clamps, strips of gauze, etc. The main desideratum is to injure the vessel wall as little as possible. The pressure of the fingers is the gentlest method and should be used in man, where possible.

If there is leakage at the site of suture a slight compression will generally cause it to cease in a few minutes.

The Circular Suture of Arteries and Veins.

Inasmuch as the lateral suture was not successful in large transverse wounds of vessels and in cases where the edges of the wound were crushed or otherwise injured, attempts were made in such cases after resection of the vessels, and in complete transverse wounds of vessels, to unite the ends of the vessels, by the simple circular suture, by protheses of various kinds or by invaginating one end into the other.

The circular suture of arteries.—The first experiments of this nature were those of Robert Abbe of New York, who published his results in 1894.

Abbe divided the femoral artery of a dog and united it again by tying the ends together over a small hourglass-shaped tube of thin glass. The immediate result of the operation was very favorable, for the circulation of the leg was re-established as soon as the clamps were removed and the dog recovered promptly. After some time the artery was removed and examined. The tube was found lying free in the lumen of the vessel which had become occluded a short distance below it. Abbe united the divided aorta of a cat in a similar manner and afterwards exhibited the animal, thinking that its survival demonstrated the patency of the aorta. This vessel, however, might have become gradually occluded without inconvenience to the animal.

In 1896 Briau and Jaboulay made ten experiments with the circular suture of carotid arteries in dogs, the ends of the vessels being united with U-shaped sutures, which everted the edges and approximated intima to intima. None of the experiments were successful, all of the vessels becoming thrombosed. They later tried the method on a larger vessel, namely the carotid of a donkey, with perfect success. This method was tried in 1900 by Salomoni, who claimed the honor of discovering it.

Murphy in 1897 published a very interesting and important article in which he detailed his numerous experiments with the suture of arteries and described a new method for the union of completely divided vessels. This method, which is said to give a more solid union than the simple suture, consists in invaginating one end of the vessel a short distance into the other and is done in the following way: After applying Billroth clamps armed with rubber, the artery is divided and the proximal end is invaginated into the distal by means of three or four double-needled silk sutures which include only the adventitia and media of the proximal end, but are passed through the entire thickness of the distal end. When these

sutures are drawn up and tied the ends are easily invaginated and fastened in this position. After the invagination is completed, the free edge of the distal end is sutured to the proximal by several interrupted sutures which include only the adventitia and media of the proximal end, but the entire thickness of the distal. The invagination is sometimes facilitated by splitting the distal stump longitudinally for a short distance.

This method was tried on the carotids of dogs three times, on the carotids of calves four times and on the carotids of sheep four times, once on the femoral artery and abdominal aorta of dogs. Only three of these cases were successful, thrombosis occurring in the others. The unfavorable results were thought to be due in a large measure to the small caliber of the vessels which were used.

Murphy also made a few experiments with the simple suture of arteries, the carotids of sheep being sutured twice, the carotids of dogs and calves once each and the abdominal aorta of a dog once. The continuous suture was used four times and the interrupted suture once. Only one of the five experiments was successful.

The invagination method was tried by DÖRFLER four times, twice in the carotids and twice in the femorals of dogs. In three cases thrombosis occurred; in the other case the lumen was unobstructed when the animal died of a venous hæmorrhage only three days after the operation.

In discussing Murphy's paper at the International Medical Congress in Moscow in 1897 NITZE demonstrated some small ivory protheses, resembling those later described by Payr. They consist of small ivory cylinders over which the ends of the vessel are slipped in such a way as to approximate intima to intima. A simple ligature holds them in this position.

In 1898 GLUCK, who had done pioneer work with the lateral suture of arteries, described a new method of circular suture. After exposing the artery and applying clamps armed with rubber, a small section of the artery was excised and slipped over one of the ends in the manner of a cuff; the ends of the vessel were sutured together with interrupted sutures which included only the adventitia and media, and then the resected portion was drawn over the line of suture and fastened thus with a few stitches. Instead of using a section of the artery to be sutured, rings of rubber and decalcified bone or a section of vessel from the same or another animal can be used.

PAYR, fearing that a simple circular suture could not withstand the pressure within large arteries devised a method, which he published in 1900, of uniting divided vessels by invaginating the ends over extra-vasal protheses of magnesium, which is absorbable in the body. If the vessel is an artery, the central end is invaginated into the peripheral, if a vein, the peripheral end is invaginated into the central. The protheses consist of hollow cylinders of magnesium, which have very thin walls and vary from .3 to 1 cm. in length. On the outer surface of the cylinder, near one end, there is a small groove, one-third to two-thirds of a millimeter deep, in which the ligature is placed. The method, as applied to arteries, is carried out as follows: After provisional closure and division of the artery, the

central end is drawn through the cylinder, which just fits over the vessel, by means of three sutures placed in the end of the vessel, which, after being drawn through the cylinder, is everted over it and fastened thus with a ligature of fine silk. The peripheral end is then drawn over the everted cuff and also fastened with a ligature, broad surfaces of endothelium being thus approximated. Payr thinks the fact that the prothesis is absorbable is of great importance. This property of the prothesis is probably of very little importance, for it requires from two to four weeks, or even longer, to be completely absorbed.

Payr, who tried the method on the carotids of dogs and pigs, says it can be done very easily and quickly and claims to have obtained very good results with it; however he does not state how many experiments he has made and makes no reference to any journal of experiments. The article is illustrated with schematic drawings, all of his preparations having been destroyed in a fire.

In an article published in 1904 Payr, on the strength of the experiments of others with it, notably those of Höpfner, champions his method and says the unsuccessful experiments of Salinari and Virdia, Jensen, and Reinsholm were due to the fact that they did not proceed according to his directions.

In 1901 BOUGLÉ performed a few experiments with circular suture of the carotids of dogs. He first used the method of Murphy, invaginating the ends by means of U-shaped sutures. The vessels, however, were so small that obliteration of the lumen always occurred. He then tried a new method, invaginating the ends only a few mm. and fastening them thus by interrupted sutures, which included only the media and adventitia. He mentions one case, in which both carotids were sutured, one by this method, the other by simple end to end union with interrupted sutures which did not include the intima. When examined 15 days after operation both vessels were patent, the intima was smooth and no clots were present.

In 1902 articles upon the circular suture of arteries by Salvia, Salinari and Virdia, Carrel, Thomaselli, and others appeared.

SALVIA made numerous experiments upon the femorals of dogs and the carotids of donkeys and sheep with special reference to the process of healing in wounds of arteries. He employed the end to end suture with fine silk, after resecting considerable lengths of the vessels. In none of the cases did the lumen remain patent. He examined the specimens histologically and found that, with the exception of the elastic fibers, there was a complete restitution of the vessel wall.

The object of the experiments of SALINARI and VIRDIA was: (a) To test the methods most often tried in animals and man and from the results to determine which offers the best chance of restoring the function of the vessel; (b) to investigate the healing process microscopically and see whether the arterial walls will be sufficiently strong at the sutured point. The experiments, about 30 in number, were done on large dogs, the carotid and femoral arteries being generally used, the abdominal aorta being used twice. With the exception of a few partial transverse and

longitudinal sutures, the sutures were done on completely divided arteries. For provisional hæmostasis various clamps were used, but, finding these unsatisfactory, they constructed a special clamp with parallel blades, regulated by a thumb screw, which proved very satisfactory.

Of 16 sutures done according to Murphy's method, six became infected and the results were negative, six healed with mural or canalized thrombi; in two the lumen remained pervious, though considerably narrowed, and in two others the site of suture presented an almost normal appearance. The protheses of Payr were tried three times, two of the animals died of infection, the other of secondary hæmorrhage.

The authors conclude that suture is preferable to ligation in wounds of large size and that in cases of complete transverse wounds invagination is the best method, although their results would hardly justify these conclusions. In cases of *restitutio ad integrum* the vessel wall is richer in muscle cells and elastic fibers than under normal conditions.

THOMASELLI emphasized the importance of approximating intima to intima. In his experiments, which were done on the abdominal aorta, carotid and femoral arteries of 11 dogs and the femoral artery of one goat, the endothelial surfaces were held approximated by fine clamps, which were removed in turn as the suture proceeded. Interrupted sutures, passing through all the coats of the vessel were used and the suture matrials were fine curved needles and silk thread. In seven cases there were positive results with or without narrowing of the lumen, in three the results were negative and in two others it was necessary to ligate on account of sclerosis of the vessel wall.

In an article published a year later Thomaselli says, that the best method of vessel suture is that previously recommended by Salomoni, which consists in approximating intima to intima by means of U-shaped sutures transfixing the entire wall of the vessel. He studied the process of healing in transverse wounds to determine whether there is a real *restitutio ad integrum* as Burci had already observed in the case of longitudinal wounds. Histological examination showed the following: (a) The muscular layer is completely regenerated; (b) the elastic fibers of this layer are regenerated and are more numerous at the edges of the scar and near the lumen where they do not form a real inner elastic membrane, but they replace this membrane and prevent the formation of an aneurysm; (c) neither the inner elastic membrane nor the elastic fibers of the adventitia are reformed, the latter being composed of fibrous connective tissue; (d) close up to the suture one can demonstrate the complete restoration of the three layers with hypertrophy of the muscle cells and elastic fibers.

In 1902 CARREL published a method of circular suture, which, while differing very little from certain methods previously employed, has greatly facilitated such sutures. The ends of the vessel to be sutured are first united by three tension sutures of fine silk, inserted at equidistant points on its circumference. Traction upon these sutures approximates the edges of the vessel and renders the application of a continuous suture comparatively easy. In his original communication Carrel recommended

avoiding the intima, where possible, but in his later experiments the sutures have included the entire thickness of the vessel wall. He has made no systematic study of the circular suture of divided arteries and veins but by applying his method to arterio-venous anastomoses and the transplantation of vessels and organs has obtained brilliant results.[4]

In 1903 an article by JENSEN on the circular suture of blood vessels, which was awarded a gold medal by the University of Copenhagen, was published. In this very complete and interesting article Jensen describes the various methods for uniting completely divided vessels which had been used up to that time and gives a critical review of the results obtained with them. Jensen's own experiments in which bone protheses, the magnesium protheses of Payr, and the various suture methods were tried on the vessels—mostly the internal jugular veins and carotid arteries—of horses and goats, were undertaken with a view to solving the following questions: (a) Why does thrombosis occur so often? (b) in how far does this or that method offer a better guarantee against thrombus formation.

Of three arteries united by Murphy's method two became completely thrombosed and one remained unobstructed; of three united by invagination over protheses of bone, in two the lumen was much narrowed and in the other almost obliterated; of twelve united by sutures seven were thrombosed, three were more or less constricted, and two were neither thrombosed nor constricted.

Ten veins were united by various protheses; of these eight became completely occluded and two remained patent but partly occluded. Seven veins were united by sutures; of these four were thrombosed, two more or less constricted and one neither thrombosed nor constricted.

From these results which are not very encouraging, Jensen rejects protheses and concludes that the best method of uniting completely divided vessels is to insert two or three simple interrupted or U-shaped sutures and join them by continuous sutures. He prefers silk to catgut and allows the suture to include the entire thickness of the vessel wall. He thinks thrombosis is due chiefly to infection with pathogenic organisms and says, "If we accept infection as the only cause of thrombus formation we have the best explanation of the capriciousness of the results of the experiments. This agrees also with the fact that sutures not involving the intima are more likely to succeed for infection of the lumen is more difficult if the suture does not enter it."

In an extensive article published in 1903 HÖPFNER gives statistics of the results of the ligation of large arteries and veins in man and thus points out the need of a practical method for uniting completely divided vessels. He then gives a history of the lateral and circular suture of vessels in animals and man. He experimented with the circular suture of vessels, vessel implantation and transplantation, and the replantation of amputated extremities, using the magnesium protheses of Payr.

Of six arteries united by this method, two became thrombosed and

[4] Vid. infra.

four remained unobstructed, three of these being examined eight days after operation and one four weeks after operation. The experiments with transplantation and implantation of vessels and the replantation of amputated extremities will be described later.

In 1903 AMBERG experimented with the circular suture of arteries in horses and large dogs, using the carotids, femorals, and abdominal aorta. After dividing the arteries, the ends were split longitudinally for a distance of 3 to 4 mm. so that the edges could be everted after the manner of flanges which were then sutured together intima to intima. His experiments were not very successful for in only three of the six cases was the lumen entirely preserved. In one there was a mural thrombus and in the remaining two complete thrombosis and secondary hemorrhage occurred.

In 1903 DE GAETANO tried on dogs a new method for the transverse suture of arteries. He placed a small spindle-shaped glass bobbin in the lumen of the vessel and applied the suture over the bobbin which was removed when the suture was nearly completed. This is said to greatly facilitate the suture. I have not been able to consult the original article and therefore cannot give the results of the individual experiments. According to De Gaetano histological examination of the specimens four months after suture showed a complete restitution of all of the elements of the vessel wall, including the elastic fibers.

In an article published in 1903 CHÉRIE-LIGNIÈRE reviews the various methods of arterial suture and concludes that the simple suture is only applicable to longitudinal wounds and not to transverse wounds. He describes the Payr method in detail and reports his own experiments with this method. Of six cases in which the arteries of dogs and donkeys were thus united, in four the results were good, in two there was secondary hemorrhage, once due to necrosis, once to infection. The magnesium cylinders were absorbed in 20 days. Secondary hemorrhage is prevented by strict asepsis and the isolation of only a short stretch of vessel.

In 1906 DORRANCE[8] reported three cases of complete transverse suture of arteries in animals, in which he used a continuous mattress suture, whipping over the everted edges of the artery after the mattress suture was completed. In two cases the lumen remained unobstructed, in the other complete thrombosis occurred.

The circular suture of veins.—As compared with arteries very few experiments have been made with the circular suture of veins. This is probably due to the fact that the danger of gangrene following the ligation of large veins is, as a rule, less than that following the ligation of the corresponding arteries.

V. HIRSCH[8] is said to have successfully sutured the completely divided

[8] Vid. supra.

[8] Cit. by Clermont.

femoral and jugular veins of dogs in 1881. Murphy in 1897 united the divided jugular vein of a sheep by means of a continuous suture of fine silk, the lumen of the vessel being considerably narrowed by the suture. The vein was examined 28 days later and found to be occluded by adhesion at the line of suture, but no thrombus was present.

In an article published in 1901 CLERMONT gives an historical review of venous suture and reports his experiments with the lateral and circular suture of veins. The latter were limited to two sutures of the divided inferior vena cava: In one case the ends of the vessel were united by a continuous mattress suture of fine silk, which everted the edges of the vessel and approximated intima to intima; the union was completed by suturing the everted edges together with a continuous whip-stitch of the same material. The vessel was examined a month later and its lumen found to be perfectly smooth and unobstructed. In the other case he invaginated the peripheral end a few mm. into the central and fastened them thus with fine silk sutures which were allowed to enter the lumen. When examined a month later the vein was found to be patent, but greatly contracted. From these experiments and those with the lateral suture of veins, Clermont concluded that the first method is the best for suturing veins.

PAYR claims to have obtained excellent results in the union of veins by means of his magnesium protheses, which are applied to veins just as to arteries, except that with veins the peripheral is invaginated into the central end. The method is said to be more easily applied to veins than to arteries, for their walls are thinner and therefore more readily stretched. Here again Payr fails to give the number of his experiments or any exact description thereof.

In 1903 JENSEN made 17 experiments with the union of completely divided veins, using the simple suture in seven cases and protheses of various kinds in ten. Of the seven simple sutures four remained patent; of the ten cases in which protheses were used, eight became completely thrombosed and two remained patent. In six of the sutures the following method was used: After inserting two or three tension sutures, a continuous suture including the entire thickness of the vessel wall was applied. In the other case mattress sutures were used. In only two cases was catgut employed and in both thrombosis occurred. Of the ten cases in which protheses were employed, the cylindrical rings recommended by Payr were used in seven, but in only three of these were the rings made of magnesium, the others being made of bone or decalcified bone.

The circular suture of arteries and veins in man.—Cases of suture of completely divided vessels in man have been reported by Murphy, Djemil Pascha, Krause, Kümmell, Payr, Brougham, and probably others.

In 1897 MURPHY reported the following case: On September 19, 1896, a young man received a bullet wound in Scarpa's triangle just below

Poupart's ligament. When he was first seen by Murphy on October 4, there was a marked thrill and loud bruit in this region and the pulsation in the popliteal and dorsalis pedis arteries was scarcely perceptible. At the operation on October 7, a penetrating wound was found in the femoral artery, which was almost divided, and also a small wound in the femoral vein. After closing the wound in the vein the artery was resected and united by the invagination method, the central end being invaginated into the distal for about one-third of an inch. On removing the clamps there was no leakage and pulsation immediately reappeared in the artery below the anastomosis. There was no disturbance of the circulation of the leg and the patient made a good recovery.

At the International Medical Congress in Moscow in 1897 DJEMIL PASCHA reported two cases of injury of the axillary artery treated successfully by Murphy's invagination method.

KRAUSE in 1900 reported this case in which he resected both the femoral artery and vein: In operating upon a woman, 55 years of age, for a carcinoma, the femoral vessels were found to be involved to such an extent that it was necessary to resect a portion of them. With the leg strongly flexed the ends of the vessels were then invaginated and fastened thus with sutures which did not involve the intima. Immediately after the operation pulsation could be felt in the artery distal to the suture; the leg had to be amputated later on account of gangrene.

In 1900 KÜMMELL reported two cases, in one of which he anastomosed the femoral artery, in the other the femoral vein. In removing a carcinoma of the glands of the groin the femoral artery was found to be involved to such an extent that it was necessary to resect 5 cm. of this vessel. This was done in the following manner: After freeing the vessel above and below and applying clamps armed with rubber, the diseased portion was removed and, with the leg flexed at the hip, the central end of the vessel was invaginated ½ cm. into the distal and sutured with fine silk which did not include the intima. This suture was reinforced by a second layer of sutures which included only the adventitia. After a short time distinct pulsation could be felt in the popliteal artery. The carcinoma recurred in a few weeks and death followed in four months; at the autopsy, unfortunately, nothing could be seen of the suture, for the vessel was completely destroyed by the growth.

In the second case it was necessary to resect 2 cm. of the femoral vein, likewise on account of involvement in malignant growth. The ends of the vein were united by means of a continuous suture of fine silk which doubtless penetrated the intima. After removing the clamps the circulation in the leg was re-established, and the patient made a good recovery.

In 1901 PAYR had an opportunity to try his method in man: In extirpating carcinomatous glands of the groin 4.5 cm. of the femoral vein was removed on account of involvement in the growth. The ends of the vessel were united by invagination over a magnesium prothesis after his method. The patient died three days later of pneumonia and examination showed that the lumen of the vein was fully preserved.

In 1906 BROUGHAM reported the following case: A man, 39 years

of age, received a stab wound which almost completely divided the axillary artery and vein. The vein was ligated, but the division of the artery was completed, and the ends united by invagination after Murphy's method. The patient made an uneventful recovery.

Remarks.—What has been said above, in discussing the lateral suture of vessels, regarding suture materials, the means of provisional hæmostasis, the question as to whether the suture should or should not penetrate the intima, the need of a perfect aseptic technic, etc., applies equally well to the circular suture.

The methods recommended for uniting completely severed vessels may in general be divided in two classes: (a) Those in which the simple suture is used; (b) those in which mechanical aids are employed.

The suture has been applied in various forms; some have used simple interrupted sutures and mattress sutures, others the continuous suture; some include all the coats of the vessel in the suture, others try to avoid the intima, which in veins is almost an impossibility. Murphy recommends uniting completely divided vessels by invaginating one end a short distance into the other and fixing them thus with sutures.

The mechanical aids may be divided into the extra-vasal and endo-vasal. Among the former may be mentioned various clamps, decalcified bone and ivory rings, sheaths made of sections of other arteries or veins, aluminum rings, magnesium rings, etc. The most important of these are the magnesium rings or protheses of Payr, by means of which the ends of the vessel are so invaginated that intima is approximated to intima. Among the endo-vasal aids we may mention the glass cylinders of Abbe and Gluck, the caramel cylinders of Carrel and the glass bobbins of De Gaetano. These are of no importance clinically, but are of historical interest.

Although the results of the application of the invagination methods of Murphy and Payr to vessels in man have proven very gratifying, I cannot but feel in the light of the animal experiments of Carrel, Jensen, myself, and others, that the simple suture is preferable to these more complicated pro-

cedures. The results obtained in animals by Carrel and myself have been, barring the cases in which infection occurred, almost ideal and seem to demonstrate conclusively that the sutures can penetrate the intima with impunity. The method is simple, easy, and requires no mechanical aid. It seems to me that, just as in intestinal suture we approximate endothelium to endothelium, so in blood vessel suture it is advisable to approximate intima to intima. With Carrel's method traction upon the three primary sutures, during the application of the continuous suture, approximates intima to intima more or less accurately, but the apposition might be improved by substituting U-shaped sutures for the single traction sutures and then applying the continuous suture to the everted edges, as has been suggested by Jensen. The advantages obtained by this method might, however, except with large vessels, be counterbalanced by the constriction produced.

Arterio-Venous Anastomoses.

Circular or end-to-end arterio-venous anastomosis.—The first successful arterio-venous anastomosis was performed by Gluck who united the carotid artery of a dog to the jugular vein by circular suture without thrombus formation. In 1902 Berard and Carrel divided the femoral artery in Scarpa's triangle and sutured the central end of the artery to the peripheral end of the saphenous vein. The anastomosis withstood the arterial pressure and the vein became distended and pulsated actively, but no physiological results were observed, as the animal died of infection two days after the operation. In the same year these experiments were continued by Carrel and Morel, who succeeded in anastomosing the central end of the carotid artery into the peripheral end of the external jugular vein without subsequent thrombus formation. Several weeks after the operation, when the animal was presented before the "Société nationale de médecine," the external jugular vein pulsated actively and a loud systolic murmur could be heard at the point of anastomosis. During the several months the animal was under observation the results remained satisfactory.

In 1902 San Martin y Satrustegui also experimented with the circular arterio-venous anastomosis. He made a series of experiments on dogs, operating by preference in the groin, but also in the neck and other regions traversed by large blood-vessels. The femoral vessels were separated and the central portion of the femoral vein ligated. Forceps were then applied to the central portion of the artery and the distal portion of the vein and the vessels divided; there was no bleeding from the distal end of the artery, although it was not clamped or otherwise occluded. The central end of the artery was then united to the distal end of the

vein by invaginating the artery into the vein and suturing them with catgut. On removing the clamps the arterial blood flowed into the vein and the distal portion of the artery, which had remained bloodless during the operation, in 30 to 60 seconds after the current was turned on, began to carry fluid which looked like a mixture of arterial and venous blood as though the current had been reversed. This end of the artery was then ligated, the wound closed, and the animal allowed to live. In later cases St. Martin saw the saphenous vein fill and change color as soon as the arterial blood was turned into the femoral vein.

All of the animals stood the operation well, except those whose peritoneum was invaded. One of the more vigorous dogs lived eight days with anastomosis of the carotid artery and jugular vein on both sides, death being due to hemorrhage, or asphyxiation from enormous œdema of the neck. Few of the dogs had œdema, but in many there was a hemorrhage on the eighth day, which was often fatal. As to the cutaneous wound, it healed usually by first intention, sometimes there was a little suppuration, and in two or three cases a real phlegmon. The specimens were examined at periods varying from 48 hours to 20 days after the operation. The vessels were found completely obliterated by extensive thrombi, which, in the late examinations, were already organized. In one case the vessel remained pervious for two days, but in some instances coagulation took place even before the current was turned on.

In 1903 EXNER undertook certain experiments with the intention of studying the changes which veins undergo, under arterial blood pressure. In four dogs he united the central end of the carotid artery to the peripheral end of the external jugular vein by means of the magnesium protheses of Payr. The wounds healed without reaction, but when examined two to six weeks after the operation, the vessels were found to be completely thrombosed. HÖPFNER in 1903 also experimented with arterio-venous anastomoses, using the protheses of Payr. In all of his cases there was thrombus formation which he attributed to degeneration of the thin vein wall, produced by the high arterial tension.

In 1905 the experiments begun in France by Carrel and Morel were continued in this country by CARREL and GUTHRIE, and, with improved technic, various arterio-venous anastomoses were done with very successful and interesting results. The technic is thus described by Carrel: "The threads and needles were the finest and strongest obtainable. The threads were sterilized in vaseline and applied when heavily coated with the same. The vessels were handled very gently and the endothelium was protected from drying by isotonic sodium chloride solution or by sterilized vaseline. No dangerous metallic forceps were used. The greatest care was exercised to obtain accurate and smooth approximation of the endothelium of the vessels. Finally, we developed a technic which is equally well adapted for arterio-arterial, veno-venous or arterio-venous anastomoses, and which yields uniformly successful results."

Circular or end-to-end arterio-venous anastomoses may be divided in two classes; viz., (a) uniterminal, and (b) biter-

minal arterio-venous anastomoses. The former will be discussed now, but the latter will be considered when we describe the implantation and transplantation of arteries and veins.

Concerning uniterminal anastomoses Carrel and Guthrie write as follows: "The termino-terminal anastomosis may be performed in nearly all cases even when the size of the vessels differs greatly. An artery may be easily united to a vein of twice its caliber. On the contrary, it is more difficult to unite a small vein to a large artery, for the venous wall is easily folded, while the artery on account of its thick walls is not. The more nearly similar the diameter of the vessels, the more easily successful anastomosis may be performed. When the vein is much larger than the artery and the consequent foldings of the vein in making the anastomosis are irregular, as may happen if the operation is performed without sufficient care, hæmorrhage occurs at the line of union. Fibrin may be deposited in the bottom of the foldings and in the miniature gaps occurring between the endothelial coats of the artery and vein. Therefore, when the difference in size of the artery and vein is too great, instead of end-to-end anastomosis, it is better to perform lateral implantation of the end of the vein into the wall of the artery.

"This termino-lateral arterio-venous anastomosis is more difficult than the former. It should be used only when the end-to-end anastomosis seems inadvisable, owing to the difference in size of the vessels or when the experimental result sought for indicates it. For instance, when a segment of intestine is transplanted into the neck for the purpose of establishing communication between the cut ends of the œsophagus, the end-to-end anastomosis of the intestinal vein to the jugular vein is impracticable, owing to the enormous difference in the size of the vessels. It then becomes necessary to make a lateral implantation of the end of the small vessel on the wall of the jugular vein. Or this lateral implantation is performed in order to obtain certain modifications of circulation, as, for example, lateral implantation of the central end of the external jugular vein on the common carotid artery, in order to diminish the amount of blood in the peripheral portion of the artery.

"Although the termino-lateral anastomosis is somewhat more difficult than the end-to-end anastomosis, it is by no means impracticable on this account. By making a triangular opening larger than the lumen of the vein, through the wall of the artery, and taking care to have an accurate approximation of the endothelial surfaces of the vessels, the anastomosis is very satisfactory, as absolutely no blood escapes and no stenosis of the vein is produced.

"A third kind of anastomosis, more rarely used than the kinds above described, may also be mentioned. When the vein is exceedingly small, so small that a direct anastomosis is impossible, it is dissected a far as its junction with a larger vein. The wall of this vein around the mouth of the small vessel is then resected and grafted onto the wall of the artery.

"As previously stated this paper will deal mainly with the transplantation of veins onto arteries.

"There are six possible varieties of this operation, as the central end or the peripheral end of the vein may be united to the central end, the peripheral end or the wall of the artery. But as the anastomosis of the central end of the artery to the central end of the vein is practically the same in result as lateral implantation of the artery onto a vein, and as anastomosis of the peripheral end of the vein to the wall of the artery produces practically the same results as the anastomosis of the peripheral end of the vein to the central end of the artery, they do not deserve special mention. Four varieties only will therefore be described.

"1. *Union of the central end of the vein to the peripheral end of the artery.*—Anastomosis of the central end of the external jugular vein to the peripheral end of the common carotid artery is an example of this kind of operation. It produces a vessel composed in its upper portion of the carotid artery and in its lower portion of the external jugular vein. The pressure in this portion of the artery becomes lower than the normal blood pressure and the direction of the blood stream is reversed. The jugular carries toward the heart red, instead of dark blood. As a result, functionally, the carotid artery becomes a vein filled with red blood, being comparable in this respect to the pulmonary vein. It is probable that the wall of the artery undergoes marked anatomical changes. Owing to the lowering of the blood pressure, its wall may become thinner and the elastic and muscular layers modified, but at the present time we cannot go further into the point. But, as we have a dog in good health upon which this operation was performed nearly seven months ago, we shall subsequently be enabled to discuss it further.

"2. *Union of the central end of the vein to the wall of the artery.*—It is evident that after this operation a large part of the red blood of the artery returns toward the heart through the veins. In several cases the central end of the external jugular vein was united to the wall of the carotid artery. An abundant portion of the red blood flowed into the vein through the anastomosis with a strong thrill. The vein retained its venous functions, *i.e.*, it conveyed blood toward the heart, but was filled with arterial blood. The artery also retained its normal functions, but its blood pressure was lowered. Tracings were taken, and they showed that after the establishment of the circulation through the anastomosis, the blood pressure in the artery is markedly diminished. This result is quite natural, for the lateral implantation of the central end of the jugular onto the wall of the carotid artery permits of a kind of continuous hemorrhage from the carotid into the vein. When this operation is made on the jugular and the carotid it does not apparently alter the character of the circulation in general.

"3. *Union of the peripheral end of the vein to the peripheral end of the artery.*—This operation was performed on arteries having no, or very small collaterals. The result was the reversal of the circulation through the vein. The artery becomes filled with dark blood, venous in character. If, for instance, the peripheral end of the right renal vein be united to the peripheral end of the left renal artery, the dark blood from the right renal vein would flow through the left renal artery, the left kidney, the left renal vein and thus into the vena cava.

" 4. *Union of the peripheral end of a vein to the central end of an artery.*—It is evident that, from a functional point of view, the operation transforms the vein into an artery. Several series of experiments were performed. The external or internal jugular or the thyroid veins were united to the carotid artery; the femoral or long saphenous veins to the femoral artery; and the inferior vena cava to the aorta.

"*The transplantation of the peripheral end of the external jugular vein onto the central end of the common carotid artery.*—The right external jugular vein was exposed, thoroughly dissected and cut near the root of the neck. Its peripheral end was inserted between the sterno mastoideus and the sterno hyoideus muscles and united behind the trachea to the central end of the left carotid artery. On release of the hæmostatic clamps, the vein became filled with red blood and pulsated like an artery, it being transformed from a functional standpoint into an external carotid artery. The vein is able immediately to perform the more important arterial functions. Its wall adequately supports the increased blood pressure. Even when the carotid artery is anastomosed to a more delicate vein, such as the internal jugular or thyroid, the sudden increasing of the pressure apparently does not injure the wall. In size the vein always appears to be very much enlarged. Clinically, this operation does not produce general or local symptoms if it deals only with vessels like the carotid and the external jugular vein. Even when the central end of the carotid is anastomosed to the peripheral end of the internal jugular vein the dog manifests no abnormal symptoms. A dog on which the operation was performed three months ago is now living and appears absolutely normal in all respects."

CARREL and GUTHRIE claim to have produced an actual arteriosclerosis of an artery by suturing it into a relatively small vein. The macroscopic modifications of the artery are characterized by a slight retraction of its lumen and by a marked increase in the thickness and rigidity of its walls. The histological changes consist of an hypertrophy of the middle coat, which is due to an increase in the number and size of the muscle and elastic fibers and an hyperplasia of the interstitial connective tissue. The sclerosis of the adventitia may be regular or irregular. The same is true of the intimal sclerosis, which may present itself in the form of a regular thickening of the intima or may be much more marked in certain places than in others. The regions of greatest thickening of the intima and adventitia correspond to the places where the media is thinner. It seems that the arterial wall reacts first by an hypertrophy of the muscle layer and that the sclerosis of the intima and adventitia comes later. In a case observed three months and ten days after the operation the hypertrophy of the muscle was strongly marked, whereas, the intimal sclerosis was slight. In another case observed six months after operation the muscular hypertrophy was somewhat greater than in the preceding case, while the intimal sclerosis was much greater. No atheromatous lesions were observed.

When arterial tension is lowered by anastomosing an artery into a large vein the wall of the artery becomes thinner and its lumen larger. The muscular and elastic constituents of the medial coat diminish in number and volume.

Lateral arterio-venous anastomosis.—After his experiments with end-to-end arterio-venous anastomoses had failed, and arguing that arterio-venous aneurysms are well borne in man, San Martin y. Satrustegui in 1902 began to experiment with the lateral anastomosis of arteries and veins in goats. After opening the carotid artery and internal jugular vein in the neck, temporary hæmostasis was produced by small rubber tubing placed about the vessels at either end of the wound and openings 1 cm. long made in the vessels. The edges of the openings were then united by means of continuous sutures of fine silk, the posterior row of sutures apparently being placed from within the lumen. Two animals were thus operated upon and the result was said to be the same in both cases, though only one section was described. In this case which was examined three months after the operation, the carotid pulsated strongly and retained its original dimensions; the vein, however, was atrophied and almost empty of blood proximal to the anastomosis, but peripheral to the anastomosis was distended with dark blood and did not pulsate. The site of the anastomosis could hardly be determined by simple inspection, but seemed to correspond to the point where the vein suddenly became contracted. No opening could be demonstrated by injecting water into the vessels. Microscopic examination showed that a small opening persisted.

Arterio-venous anastomoses in man.—From these experiments, although they could scarcely be called successful, St. Martin concluded that such an operation might be of value in treating gangrene due to arterial sclerosis. He tried it clinically in two cases. The first case was a man, 52 years of age, with gangrene of the toes extending onto the metatarsus. No pulsation could be felt in the dorsalis pedis, posterior tibial or even in the popliteal artery. The femoral pulsated strongly in Scarpa's triangle. An incision was made in Scarpa's triangle and the artery easily isolated, but the vein was freed with difficulty, being rather adherent. Temporary hæmostasis was produced by rubber tubes held with clamps. Openings 8 mm. long were then made in the vessels and a fairly satisfactory anastomosis obtained. After removing the ligatures the arterial blood passed through the artery to the limb, but the vein did not change color, either because the anastomotic opening was too small or because the walls of the vein had lost the little elasticity which they normally possess. The wound was closed and the gangrenous portion of the foot removed. The immediate result of the operation was fairly satisfactory; the pains became less, either because the gangrenous portion was removed, because the nerves had been separated from the vessel sheath to which they were quite adherent, or because, thanks to the anastomosis, the leg was better nourished. Unfortunately, this condition did not continue long and symptoms appeared which required amputation of the leg through the calf. The arteries were greatly sclerosed; the vein, however, appeared normal with the exception of some atrophy, probably from disuse. St. Martin thought the veins might have assumed the function of arteries if the operation had been done earlier and been more successful. Sometime later amputation through the middle of the thigh resulted in death. The specimen showing the anastomosis was not examined, at least it is not described.

The other case was a man, 66 years old, who had gangrene of the toes. The same procedure was adopted as in the foregoing case. The artery and vein were so adherent to each other that, for hæmostasis, it was necessary to place the rubber bands about the two together. The nerve, however, was carefully separated. Very small openings were made in the artery and vein, which were united by continuous sutures. After removing the ligatures the vessels filled out, but the walls of the vein were so thick that one could not see whether arterial blood passed into the vein through the small wound. The wound in the groin was closed and the foot amputated. The patient made an uneventful recovery, but nothing is said of the subsequent behavior of the vessels.

In 1902 JABOULAY reported the following case: A man, aged 47, had senile gangrene of the right foot which required amputation, first of the foot and then of the thigh. Sometime later gangrene began in his left foot and Jaboulay performed a lateral anastomosis of the femoral vessels in Scarpa's triangle. Thrombosis, which was attributed to the presence of an arterio-sclerotic placque, occurred at the site of suture, and it became necessary to amputate through the thigh.

In 1903 GALLOIS and PINATELLLE, assistants of Jaboulay, reported this case and published the results of certain experiments, which they had made, to investigate the possibility of a reversal of the circulation in the head, arms, and legs. In order that such a reversal of circulation may take place they pointed out that the following obstacles must be overcome: (a) The valves; (b) the numerous venous anastomoses, which create short circuits and lower the blood pressure; (c) the resistance of the capillaries. Their experiments were done on the cadaver. A colored fluid was injected under pressure into the main vein of the member, but immediately returned by the other veins. After these were occluded it was impossible to force the fluid into the main vein, although considerable pressure was used. They concluded that, experimentally the circulation through the main vein of a limb, in a direction opposite to that of the normal current is prevented by the valves. They realized the fact, however, that, clinically, the valves can be forced and the current reversed in the veins, for they had observed cases of arterio-venous aneurysm, in which the veins of the limb, even at considerable distances from the aneurysm, were markedly dilated and pulsated actively.

Carrel and Guthrie, who attribute the failure of the experiments of Gallois and Pinatelle to the fact that they operated upon the cadaver and not upon living tissues, which have a great adaptive power, seem to have proven that a reversal of the circulation in a limb of a dog is possible by establishing an end-to-end arterio-venous anastomosis. An experiment on a dog showed that three hours after a *termino-terminal* anastomosis of the central end of the femoral artery to the peripheral end of the femoral vein, the veins of the thigh, the leg, and the foot were filled with red blood, and that the dark blood returned to the heart through the arteries. They found that: (a) The valves prevent, at first, the reversal of the circulation in the veins; (b) after a short time the valves gradually give way and the red blood flows through the veins as far as the capillaries; (c)

finally, it passes through the capillaries and the arteries are filled with dark blood. Probably the dark blood also returns from the capillaries toward the heart through some of the veins; (d) practically complete reversal of the circulation is established about three hours after the operation. However, when a *lateral* arterio-venous anastomosis has been done, the larger part of the arterial blood, instead of going toward the capillaries, returns to the heart through the central end of the vein and at the same time the arterial blood pressure is lowered. Experiments have shown that: (a) After a lateral arterio-venous anastomosis a very large portion of the red blood returns immediately toward the heart through the central end of the vein; (b) the peripheral portion of the vein and its branches are distended and pulsate, but the valves are not forced and the red blood does not circulate through them; (c) three hours after the operation all the valves are yet competent and no beginning of a reversal of the circulation can be detected.

If this be true very little can be expected from the treatment of senile gangrene by lateral arterio-venous anastomosis.

In 1906 HUBBARD reported the following case, in which he performed a crossed arterio-venous anastomosis of the femoral vessels for senile gangrene of the toes. The patient, a man 80 years old, was admitted to the hospital with dry gangrene of the middle toe of the right foot. There was a general arteriosclerosis and no pulsation could be felt in the dorsalis pedis of this foot. In spite of appropriate treatment the gangrene extended and involved the neighboring toes. Operation: The femoral vessels were exposed at the apex of Scarpa's triangle and a crossed arterio-venous anastomosis performed by invaginating the central end of the artery into the peripheral end of the vein and the peripheral end of the artery into the central end of the vein, and suturing them thus with fine Pagenstecher's thread. After the first anastomosis had been completed, and the means of provisional hæmostasis removed, the vein partially filled and pulsated slightly. During the manipulations the controlling tourniquet was pulled off the peripheral end of the artery and a considerable amount of dark, venous-looking blood escaped. It is hardly possible, however, that the circulation could have been reversed in such a short time. The cutaneous wound was closed with silk-worm gut and a plaster cast applied with the thigh flexed on the body to relieve tension on the vessels.

The patient made a good recovery, but the gangrene subsequently extended to the tarso-metatarsal joint, where a line of demarcation formed. At this time the author thought he was justified in making the following deductions: "Inasmuch as the circulation in the leg before operation was sufficiently poor to permit gangrene of the toes, and inasmuch as the femoral artery had been divided in Scarpa's triangle thus permitting collateral circulation only through the profunda, it was fair to suppose that very little blood would have reached the lower leg through the collateral circulation, and that the gangrene would have rapidly involved the leg unless as a result of the operation the veins were carrying arterial blood." The lower portion of the leg and foot were amputated some

time later. At this operation, which was performed without a tourniquet, the anterior and posterior tibial arteries were found to contain arterial blood, which spurted from the cut ends with fairly good force, and the veins did not appear to contain any arterial blood. These findings probably vitiate the previous deductions.

Implantation and Transplantation of Arteries and Veins.

In 1896 Briau and Jaboulay experimenting upon animals, after having removed small sections of arteries reimplanted them by circular sutures. The vessels were examined three or four days after the operation, and in all the cases occluding thrombi were present. In an article published in 1898 Gluck mentions having transplanted a portion of the jugular vein into the carotid artery of a dog. The section of vein healed in and there was no secondary hemorrhage, but thrombosis occurred.

In 1903 Exner experimented with the transplantation of blood vessels using the magnesium protheses of Payr. In six animals he transplanted portions of the external jugular vein into the carotid artery, but in all the cases thrombosis took place. In two dogs pieces of jugular vein, 4 cm. long, were transplanted into the opposite jugular vein, and in two other animals the same was done with the carotid arteries. In these cases also thrombosis was always present when the specimens were examined. Exner thought the failure of the latter experiments was due to the poor nourishment of the transplanted vessel, resulting from disturbance of the vasa vasorum.

In the same year Höpfner performed some experiments with the implantation and transplantation of vessels, and obtained more or less successful results. He likewise employed the magnesium protheses of Payr. Of two cases, in which sections of the carotid were removed and reimplanted, one was successful when examined four weeks after the operation. In one dog a section of the carotid 3 cm. long was transplanted into the femoral artery and a section of the femoral of the same length into the carotid; when examined eight weeks later there was no thrombosis, almost no constriction of the vessels, and their intima was smooth. In another experiment a portion of the carotid of one animal was transplanted into the femoral of another animal, and a portion of the femoral of the latter into the carotid of the former. The second experiment was successful, and the first was not, probably due to the fact that the wound in the neck healed per primam, whereas the wound in the groin healed by granulation. In 10 experiments, in which sections of veins were transplanted into arteries, although the technic was the same as in the other experiments and care was taken to have the valves of the veins point in the right direction, thrombosis always occurred. Höpfner concluded that such transplantations offer little prospect of being successful, for, when the current is turned on, there is a marked dilatation of the vein, and more or less stagnation of the blood, which leads to thrombus formation. In three experiments sections of vessels were transplanted from one animal species to another, but the result in all cases was negative.

Carrel and Guthrie, who, in this branch of vascular surgery also, have obtained the most remarkable results, speak of an autoplastic transplantation, when the section of vessel is taken from one vessel and transplanted into another vessel of the same animal, a homoplastic transplantation, when the section of vessel is taken from another animal of the same species, and a heteroplastic transplantation when it is taken from an animal of a different species. As a matter of fact, clinically it would be unnecessary to perform any but an autoplastic transplantation, for we can easily extirpate a short section of vein without interfering with the general circulation.

Transplantations may be (a) complete or (b) incomplete. In complete transplantations the segment of vessel is completely excised and then sutured between the cut ends of the other vessel. In incomplete transplantations the middle portion of the segment of vessel is allowed to remain attached to the surrounding tissues and to its branches; for example, a section of femoral vein can easily be isolated without disturbing its connection with the surrounding tissues and sutured between the cut ends of the accompanying femoral artery.

On removing the hæmostatic clamps, after transplanting a segment of vein into an artery, the segment of vein becomes distended with red blood until it is usually considerably larger than the artery, but, although they may be quite thin, its walls adequately support the arterial blood pressure. The pulsation in the vein is less marked than in the artery, for the vein is usually so distended that there is little excursion of the pulse wave. When the transplantation is incomplete and the segment of vein has branches, these branches do not immediately transmit arterial blood. At first they are filled with venous blood, which becomes displaced by the arterial blood as the valves are gradually forced. The branches then virtually become arteries.

Replantation and Transplantation of Organs and Limbs.

The replantation of an organ or limb consists in removing it, replacing it, and re-establishing its circulation by vascular anastomoses. The transplantation of an organ or limb consists in its removal and transplantation into another animal

or a different portion of the same animal, its circulation being re-established by vascular anastomoses.

In 1902 ULLMANN removed a dog's kidney and transplanted it into his neck, the renal artery being united to the carotid artery and the renal vein to the external jugular vein by means of Payr's protheses. The experiment was said to be successful, the kidney secreting normally after the operation. He does not state, however, how long this condition continued. Three months after this report, Ullmann reported having transplanted the kidney of one dog into another and the kidney of a dog into a goat. He exhibited the latter animal, and demonstrated the functionating kidney. When asked concerning the fate of the dog into whose neck the kidney had been transplanted, he did not say how long the animal had lived or how long the kidney had functioned. He said, however, that the kidney had been removed and on macroscopic examination several necrotic areas were seen; otherwise the kidney seemed normally nourished and had grown to the surrounding tissues.

In 1902 DECASTELLO also reported experiments with the transplantation of kidneys. He extirpated the kidney of a large dog and transplanted a kidney from another dog into its place uniting the vessels by means of protheses. The animal lived 40 hours during which time 1200 cc. of urine was secreted. Death was due to hæmorrhage resulting from separation of the venous anastomosis.

In 1905 FLORESCO reported certain experiments with the transplantation of kidneys. After several unsuccessful attempts he succeeded in extirpating the kidney of one dog and transplanting the kidney of another dog into its place the vessels being united by sutures. The end of the ureter was sutured into the skin incision. He does not give the ultimate results of the operation.

Since 1905 Carrel and Guthrie have made numerous experiments with the replantation and transplantation of organs and have obtained some very interesting results. One of their first experiments along these lines was the extirpation and replantation of the thyroid gland with reversal of its circulation. The right thyroid gland of a dog was dissected out and all its vessels ligated except the superior thyroid artery and vein. These vessels were divided, the gland removed and then replaced, the circulation being reversed by suturing the artery to vein and vein to artery. Eleven days after the operation the wound was opened and the gland found to be somewhat enlarged, but its hue and consistency were normal. Twenty-five days after operation the condition seemed practically the same. No histological examination was made, however. By reversing the circulation of goitres in dogs they claim to have produced a diminution in the size of the lobe operated upon and in one dog the goitre not only became smaller, but the general symptoms, referable to a hypothyroidism, largely disappeared. They think these phenomena were due to an augmentation of the circulation resulting from the reversal.

CARREL and GUTHRIE have used two methods of transplanting organs, *transplantation simple* and *transplantation en masse.*

The *transplantation simple* is the method which has been generally employed, but the objections to this method are that the nerves and their sympathetic ganglia are cut off from the organ and the veins are unduly exposed to injury, so that it is impossible to transplant such organs as the testicle and ovary by this method. To obviate these difficulties they developed the technic of *transplantation en masse,* which consists in extirpating the organ together with its surrounding connective tissues, its nerves and ganglia and its vessels with the corresponding segments of the large vessels from which they originate.

Making use of the simple method of transplantation Carrel and Guthrie have transplanted a heart, a loop of intestine, a kidney, and other organs into the neck. While the immediate result was, in most cases, satisfactory the ultimate result was usually disappointing. A kidney which was thus transplanted continued to function for some days.

The *transplantation en masse* has been used by Carrel and Guthrie in the transplantation of kidneys and ovaries. The technic of these operations is thus described by them.

Both kidneys and the upper portion of the ureters were removed from a small dog, along with their vessels, nerves, nervous ganglia, the surrounding connective tissue, the supra-renal glands the peritoneum, and the corresponding segments of the aorta and vena cava. The mass was placed in isotonic sodium chloride solution and later transplanted between the cut ends of the abdominal aorta and the inferior vena cava of a bitch. The circulation was re-established after having been interrupted one hour and a half. Clear urine flowed abundantly from the transplanted ureters which were anastomosed to the normal ones. Both normal kidneys were then removed. The dog recovered rapidly from the operation and remained in good health for eight days, during which time she secreted large quantities of clear urine, which contained no blood and was about normal in composition, the only abnormal constituent being a small amount of coagulable proteid. The dog died on the tenth day as a result of intestinal obstruction, due to a localized peritonitis on the right side of the abdomen. The circulation of both kidneys was perfect, but there was an enormous hydronephrosis on one side.

Ovaries were transplanted as follows: The specimen, consisting of ovary and a part of the Fallopian tube, united to the segments of the aorta and vena cava by a cellulo-peritoneal ribbon and the ovarian vessels, was taken from one cat and transplanted into another cat from which the corresponding tissues had been removed. The operation is said to have been successful.

Their experiments with *heteroplastic transplantations of organs* were unsuccessful, and they think that, on account of cytolysis, such transplantations are not likely to be successful.

The replantation of amputated limbs.—In 1903 HÖPFNER experimented with the amputation and replantation of the legs of dogs, uniting the femoral vessels in Scarpa's triangle by means of Payr's protheses. This was done in three animals. In the first case thrombosis occurred on the first day and gangrene followed; in the second case the circulation re-

mained intact 11 days, when death occurred under chloroform, while the dressings were being changed; in the third case thrombosis occurred on the sixth day and gangrene resulted.

CARREL and GUTHRIE have also made several experiments with the replantation of amputated legs of dogs, but none of these can be said to have been absolutely successful, for, although the circulation remained good for some days, obliteration of the vessels ultimately occurred.

AUTHOR'S EXPERIMENTS.

These experiments were begun with attempts to transplant the thyroid gland, making use of vascular anastomoses by Carrel's method. The attempts proved unsuccessful, so it was decided to apply this method to a series of arterial, venous, and arterio-venous sutures, with a view to determining in what percentage of cases we may expect a successful result.

The experiments were done on dogs of various sizes. When they could be obtained, large animals were used, but often it was necessary to make use of very small ones. The anæsthetic was ether, usually administered after a previous injection of one grain of morphine. The following technic was employed. After shaving a large area, the skin was cleaned with soap and water, permanganate of potash, oxalic acid and bichloride of mercury. The field of operation was then isolated with sterile towels and, after making the skin incision, sterile towels were clamped to the edges of the incision. The vessels were exposed, well freed and provisional hæmostasis produced by small spring clamps whose blades were armed with rubber. The vessels were then divided and prepared for suture by carefully removing the loose connective-tissue sheath about the ends of the vessel. This can be done very nicely by grasping the sheath with forceps, drawing it over the end of the vessel and clipping it off with scissors. The greatest care was exercised in handling the vessels, in order that they be injured as little as possible, and especial care was taken not to apply metallic forceps to the intima. Very fine (No. 16) straight needles and fine China bead silk were the suture materials employed, the thread being greased with or boiled in vaseline as suggested by Carrel. During the operation the

drying of the vessels was prevented by the application of normal salt solution or sterile vaseline.

The vessel sutures were done according to Carrel's method. The vessel ends were first united by three interrupted sutures equidistant from each other on the circumference of the vessel, the sutures penetrating all the coats of the vessel. By traction upon these sutures the edges of the vessels were nicely approximated and a continuous suture easily applied. It is convenient to leave the needles attached to the long ends of the primary sutures and to use these ends for the continuous suture. On turning on the current there was seldom any leakage, and when it did occur a slight compression usually caused it to cease in a few minutes. The tissues over the vessel were approximated with fine silk sutures and the skin wound was closed with a subcuticular suture of the same material. The wounds were dressed with silver foil and when the operation was on the neck a crinoline bandage was applied. When the wound was in the groin, it was usually dressed with collodion; sometimes a crinoline bandage was applied, which was usually torn off by the animal within 24 hours. Thanks are due Dr. R. R. Norris, of Washington, D. C., for assistance in many of these experiments.

Results.—The common carotid artery was sutured thirteen times. All of the sutures were perfectly successful and in no case was there the slightest evidence of thrombus formation. The femoral artery was sutured twice, thrombosis occurring both times as a result of wound infection. The external jugular vein was also sutured thirteen times, ten of the sutures being successful. (See figures appended.)

Microscopic examination of the arterial sutures at periods varying from twenty-eight to eighty-two days after the operation shows that there is a gradual restoration of the artery at the site of suture and that with the exception of the inner elastic membrane, all the elements of the vessel wall are probably regenerated. The sections of the thin-walled veins which were obtained were so distorted by the presence of the silk sutures that they were of little value for microscopic study.

The common carotid artery was sutured to the external jugular vein four times, all being successful. After the suture the veins became distended and pulsated vigorously; a marked thrill could be felt in the veins and a loud murmur heard over them. Examination of the veins one to three months after the operation showed a marked dilatation of these vessels, a thickening of their walls, and in some there were interesting placques in the intima, suggesting the changes seen in arterio-sclerosis. Microscopic examination of the walls of the veins revealed changes very analagous to those found in the walls of arterio-sclerotic arteries. In the vein of experiment 13 (see Fig. 12) the following condition was found: While all the coats of the vessel were greatly thickened, the thickening of the intima, especially in the regions corresponding to the white placques seen in the gross specimen, was very marked. The endothelial cells lining the intima were short and thick. The intimal thickening was composed of fibrous tissue fairly rich in cells. In certain places this tissue contained fewer nuclei and stained more poorly, but no atheroma was present. The thickening of the media was due to an increase in the interstitial connective tissue as well as to an increase in the size and number of its muscle cells. Where the intima was thicker the muscle cells seemed to be fewer and were separated by a considerable amount of connective tissue. The thickening of the adventitia was also well marked. There seemed to be a considerable increase in the elastic fibers of the intima, especially in the deeper portions near the inner elastic membrane, where a net-work of fine fibers was seen. In general, the elastic fibers seemed somewhat less abundant in the thicker placques, but at their edges and in their deeper layers numerous fine elastic fibers were seen, apparently invading them. The elastic fibers of the media and adventitia were diminished, but the diminution was more marked in the former.

The central end of the divided femoral artery was sutured to the distal end of the divided femoral vein four times. One case was successful; in the others thrombosis occurred. In the

successful case the leg became very much swollen after the operation and in two days was twice as large as the opposite one. The swelling gradually subsided but never entirely disappeared. The femoral vein became much dilated and marked pulsation could be felt in the saphenous vein near the foot. Examination three months after the operation showed a marked dilatation and thickening of the wall of the vein. The distal portion of the femoral artery was small, atrophic, and did not seem to be performing the functions of a vein.

In four animals a lateral anastomosis of the femoral artery and vein was made. In all the cases the immediate result was quite satisfactory; on turning on the blood stream there was no leakage, the vein became considerably distended, a thrill could be felt in it near the point of anastomosis and a humming-top murmur could be heard at some distance from the animal. The red arterial stream could be seen through the thin-walled vein, rushing into the vein and for the most part returning immediately to the heart. In only one of the animals, however, did the anastomosis remain patent, a marked thrill and loud murmur being present five weeks after the operation when the animal escaped from the paddock and was lost. In the second animal the murmur and thrill persisted for four weeks and then disappeared, examination a few weeks later showing that the anastomotic opening had healed, but that the vessels had remained patent. In the third animal, whose wound became infected, the thrill and murmur lasted only four days; examination two months later showed a thrombosis of the artery, the vein remaining unobstructed. In the fourth case the thrill and murmur persisted five or six days, death occurring on the eighth day after operation from secondary hæmorrhage.

Excision and replantation of a section of the femoral artery was done once, but thrombosis occurred. Transplantation of a section of vein into an artery was tried twice. In one instance a section of the external jugular vein was transplanted into the common carotid artery with perfect success. Examination of the specimen (see Fig. 15) twenty-six days after

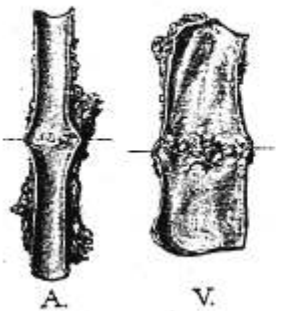
the operation showed considerable dilatation and thickening of the transplanted vein and the microscopic study of the vein revealed a condition very similar to that described above, resulting from the end to end anastomosis of the carotid artery and jugular vein. In the other case a section of the external jugular vein was transplanted into the femoral artery, but thrombosis resulted in a few days.

Transplantation of the thyroid gland was done six times, but none of these were sucessful. The failure of these experiments may be attributed to the small size of the inferior thyroid vein, whose diameter rarely exceeded two or three millimeters, and to the fact that the transplantations were undertaken before we had made any experiments with simple vascular sutures.

In reviewing our experiments we find that of thirty-one experiments upon the vessels of the neck twenty-eight were successful, whereas of twelve experiments upon the femoral vessels only two were entirely successful. This discrepancy is not difficult to explain. Wounds in the neck are inaccessible to the dog's teeth, and can be readily bandaged, the wounds being thus kept clean and dead space obliterated. In the groin, however, it is very difficult to apply a bandage which will remain in place, obliterating the large dead space which is so apt to be present and preventing movements of the leg which interfere materially with a successful vessel suture.

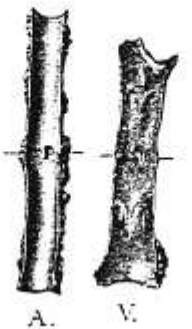
The results show conclusively that completely divided vessels can be sutured with almost uniform success, when the aseptic technic is good. The intima can be included in the suture with impunity, the application of the suture being thus greatly facilitated. Nearly all experimenters with the suture of blood-vessels have called attention to the need of a very perfect technic. I wish also to emphasize this point, for I consider infection by far the most important factor in producing thrombosis after vascular sutures. I think, as Carrel does, that there may be minor grades of infection, which, although allowing per primam healing of the wound, may be sufficient to produce thrombosis of the sutured vessels.

Fig. 1.



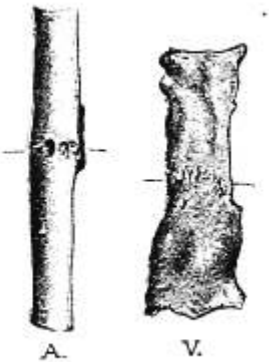
Circular suture of carotid artery and jugular vein, 28 days after operation.

Fig. 2.



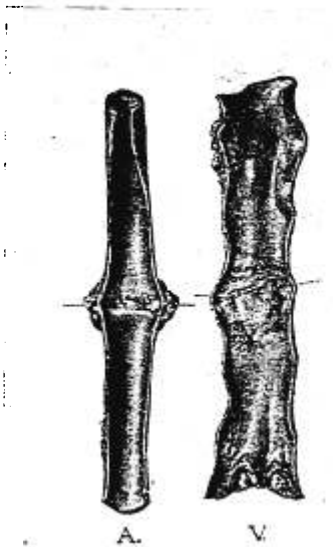
Circular suture of carotid artery and jugular vein, 42 days after operation.

Fig. 3.



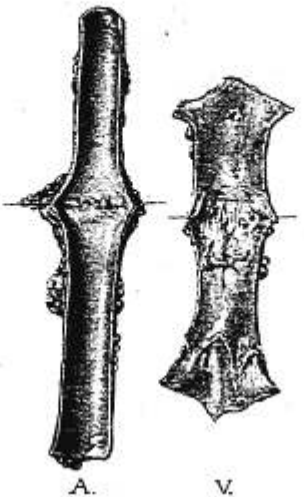
Circular suture of carotid artery and jugular vein, 35 days after operation.

Fig. 4.



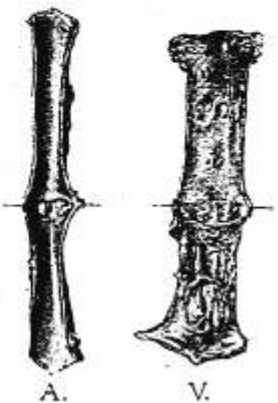
Circular suture of carotid artery and jugular vein, 82 days after operation.

Fig. 5.



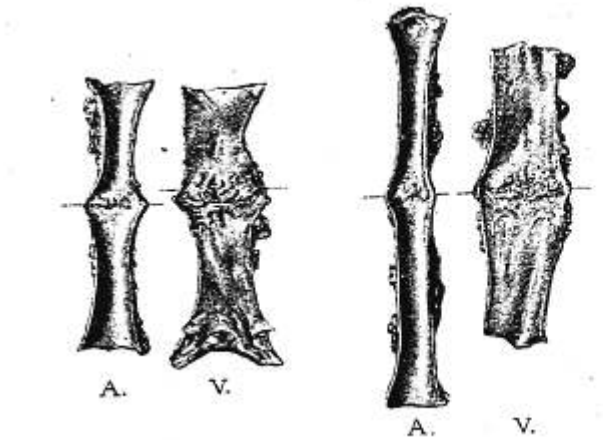
Circular suture of carotid artery and jugular vein, 48 days after operation.

Fig. 7.



Circular suture of carotid artery and jugular vein, 32 days after operation.

FIG. 6.

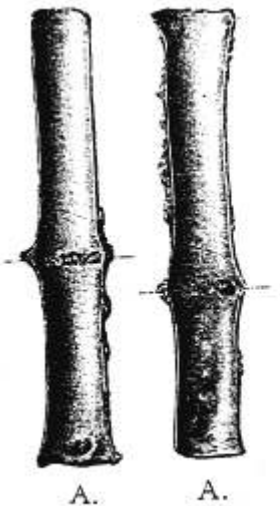


Circular suture of both carotid arteries and both jugular veins, 41 days after operation.

FIG. 8.

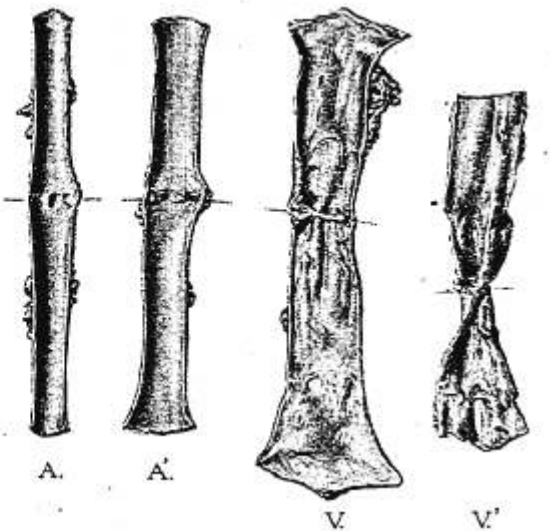
Circular suture of carotid artery and jugular vein, 26 days after operation.

FIG. 9.



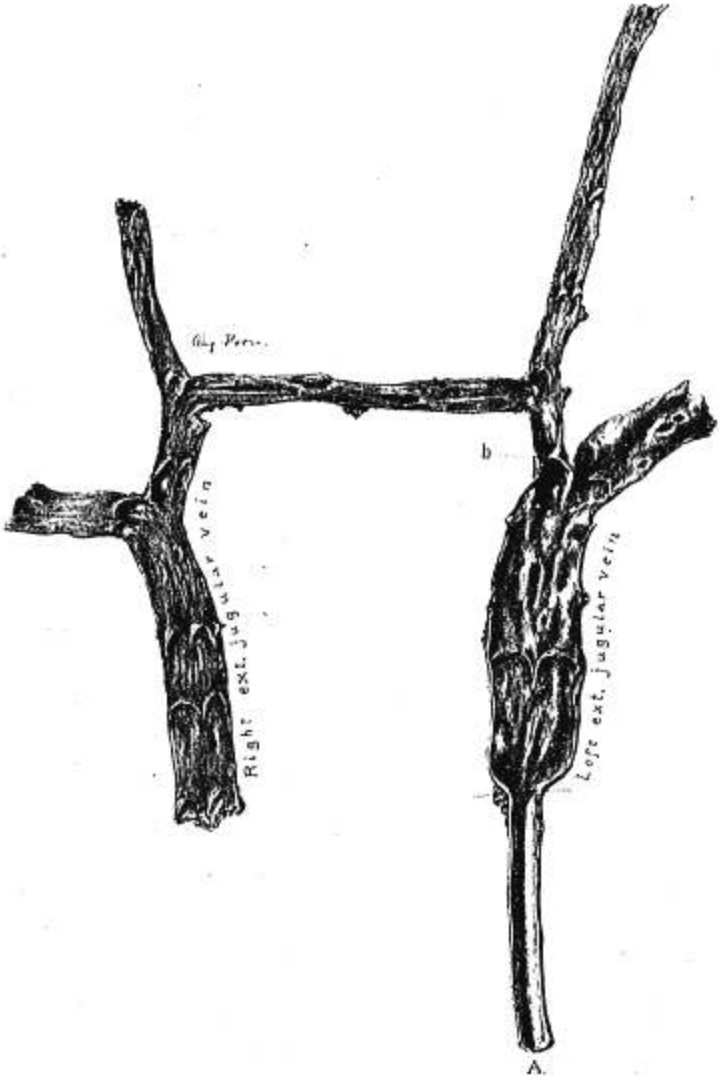
Circular suture of both carotid arteries, 18 days after operation.

FIG. 10.



Circular suture of both carotid arteries and both jugular veins, 17 days after operation.

FIG. 11.



Circular anastomosis of the left common carotid artery and left external jugular vein, 4 months after operation. As a result of arterial pressure this vein is much thickened and dilated. Small branch of vein occluded (b), probably due to valves being forced together and becoming adherent

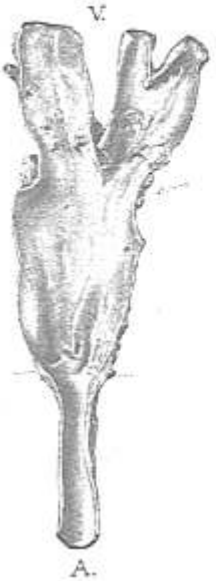
FIG. 12.

Circular anastomosis of carotid artery and jugular vein 3 months after operation. Marked sclerosis of vein.

FIG. 13.

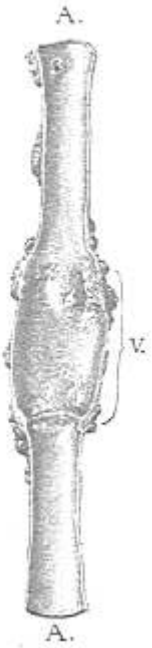
Circular anastomosis of femoral artery and vein, 3 months after operation. Marked thickening and dilatation of vein.

FIG. 14.



Circular anastomosis of carotid artery and jugular vein, 40 days after operation. Note thickening and dilatation of vein.

FIG. 15.



Transplantation of section of jugular vein into the carotid artery, 26 days after operation.